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(54) Title: GENETIC MANIPULATION OF ISOFLAVONOIDS  
(54) Titre: MANIPULATION GÉNÉTIQUE D'ISOFLAVONOIDES

## (57) Abstract

Soybean and Medicago truncatula CYP93C genes have been isolated which encode a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone. Plants can now be genetically engineered to produce isoflavones that provide potential human health benefits and increase disease resistance in plants. Isoflavones can now be produced in transgenic plants species in which isoflavones do not naturally occur, i.e., in species other than legumes. Alternatively, introducing infection-inducible isoflavonoid biosynthesis into non-legumes qualitatively complements these plants' phytoalexin defenses against microbial pathogens, whereas over-expression of the isoflavonoid pathway in legumes quantitatively increases this defense response. Finally, modifying the extend of production of isoflavonoids in legume roots positively impacts nodulation efficiency and therefore plant yield.

## (57) Abrégé

L'invention concerne les gènes CYP93C du soja et de Medicago truncatula isolés, ces gènes codant pour un cytochrome P-450 capable de catalyser la migration aryle d'une flavanone pour produire un produit intermédiaire d'isoflavanone ou une isoflavone. Il est maintenant possible de modifier génétiquement des végétaux pour produire des isoflavones susceptibles d'être bénéfiques pour l'homme et d'améliorer la résistance aux maladies chez les végétaux. On peut donc produire des isoflavones dans des espèces végétales transgéniques ne contenant pas naturellement d'isoflavones, autrement dans des espèces autres que les légumineuses. Dans une variante, on peut provoquer une biosynthèse d'isoflavonoïdes, induite par une infection, dans des espèces non légumineuses, ce qui vient compléter avec avantage la défense de la phytoalexine contre les agents pathogènes microbiens, une surexpression de la voie des isoflavonoïdes dans les légumineuses permettant par ailleurs une amélioration qualitative de cette réaction de défense. Enfin, on peut transformer positivement l'efficacité de nodulation, et donc le rendement végétal, en modifiant l'importance de la production d'isoflavonoïdes dans les racines des légumineuses.

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<b>(21) International Application Number:</b> PCT/US00/05915 <b>(22) International Filing Date:</b> 8 March 2000 (08.03.00) <b>(30) Priority Data:</b> 60/123,267 8 March 1999 (08.03.99) US <b>(71) Applicant (for all designated States except US):</b> THE SAMUEL ROBERTS NOBLE FOUNDATION, INC. [US/US]; 2510 Sam Noble Parkway, Ardmore, OK 73401 (US). <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> STEELE, Christopher, L. [US/US]; 617 Campbell, Ardmore, OK 73401 (US). DIXON, Richard, A. [GB/US]; 206 Woods Lane, Ardmore, OK 73401 (US). <b>(74) Agents:</b> HANSEN, Eugenia, S. et al.; Sidley & Austin, Suite 3400, 717 N. Harwood, Dallas, TX 75201-6570 (US).		<b>(81) Designated States:</b> AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>With international search report.</i> <i>Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>
<b>(54) Title: GENETIC MANIPULATION OF ISOFLAVONOIDS</b>  <div style="text-align: center;"> <p> <math>\text{R=H; liquiritigenin}</math>      <math>\text{R=OH; naringenin}</math>      <math>\text{2-hydroxyisoflavanone}</math>      <math>\text{R=H; daidzein}</math>      <math>\text{R=OH; genistein}</math> </p> </div> <b>(57) Abstract</b> <p>Soybean and <i>Medicago truncatula</i> CYP93C genes have been isolated which encode a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone. Plants can now be genetically engineered to produce isoflavones that provide potential human health benefits and increase disease resistance in plants. Isoflavones can now be produced in transgenic plants species in which isoflavones do not naturally occur, i.e., in species other than legumes. Alternatively, introducing infection-inducible isoflavonoid biosynthesis into non-legumes qualitatively complements these plants' phytoalexin defenses against microbial pathogens, whereas over-expression of the isoflavonoid pathway in legumes quantitatively increases this defense response. Finally, modifying the extend of production of isoflavonoids in legume roots positively impacts nodulation efficiency and therefore plant yield.</p>		

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**Description**

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## GENETIC MANIPULATION OF ISOFLAVONOIDS

### TECHNICAL FIELD OF THE INVENTION

The invention relates to gene manipulation in plants.

### BACKGROUND OF THE INVENTION

The flavonoids are a major class of phenylpropanoid-derived plant natural products. Their fifteen carbon (C<sub>6</sub>-C<sub>3</sub>-C<sub>6</sub>) backbone can be arranged as a 1,3-diphenylpropane skeleton (flavonoid nucleus) or as a 1,2-diphenylpropane skeleton (isoflavonoid nucleus). Although 1,3-diphenylpropane flavonoid derivatives are almost ubiquitous among terrestrial plants, the 1,2-diphenylpropane isoflavonoids are restricted primarily to the Leguminosae, although they occur rarely in other families such as the Apocynaceae, Pinaceae, Compositae, and Moraceae (Tahara, S. and R. K. Ibrahim, 1995, "Prenylated isoflavonoids - an update," *Phytochemistry* 38: 1073-1094).

The limited taxonomic distribution of the isoflavonoids is directly related to the occurrence of the enzyme complex isoflavone synthase (IFS), which catalyzes the aryl migration reaction leading to the formation of an isoflavone from a flavanone. While flavanones are ubiquitous in higher plants, the IFS reaction, which is a two-step process specific for isoflavonoid biosynthesis (Kochs, G. and H. Grisebach, 1986, "Enzymic synthesis of isoflavones," *European J Biochem* 155: 311-318), is limited to the Leguminosae and the other diverse taxa in which isoflavonoids are occasionally found.

The presence of isoflavonoids provides several advantages to plants. One such advantage is provided by the function of isoflavonoids as antimicrobial phytoalexins in plant-microbe interactions. For example, the simple isoflavones daidzein and genistein act as initial precursors in the biosynthesis of various antimicrobial isoflavonoid phytoalexins in a wide variety of legumes (Dixon, R. A. and N. L. Paiva, 1995, "Stress-induced phenylpropanoid metabolism," *Plant Cell* 7: 1085-1097). Isoflavonoid compounds have been shown to accumulate in infected plant cells to

5 levels known to be antimicrobial *in vitro*. The temporal, spatial and quantitative  
aspects of accumulation are consistent with a role for these compounds in disease  
resistance (Rahe, J. E., 1973, "Occurrence and levels of the phytoalexin phaseollin in  
10 relation to delimitation at sites of infection of *Phaseolus vulgaris* by *Colletotrichum*  
5 *lindemuthianum*," *Canadian J Botany* 51: 2423-2430; Hadwiger, L. A. and D. M.  
Webster, 1984, "Phytoalexin production in five cultivars of pea differentially resistant  
to three races of *Pseudomonas syringae* pv. *pisi*," *Phytopathology* 74: 1312-1314;  
15 Long, et al., 1985, "Further studies on the relationship between glyceollin  
accumulation and the resistance of soybean leaves to *Pseudomonas syringae* pv.  
10 *glycinea*," *Phytopathology* 75: 235-239; Bhattacharyya, M. K. and E. W. B. Ward,  
1987, "Biosynthesis and metabolism of glyceollin I in soybean hypocotyls following  
20 wounding or inoculation with *Phytophthora megasperma* f. sp. *glycinea*," *Physiol and*  
*Mol Plant Pathology* 31: 387-405). Moreover, it has been reported that many plant  
pathogens are much more sensitive to phytoalexins of non-host species than they are  
25 15 to the phytoalexins of their natural hosts, because they can often detoxify the host's  
phytoalexins. (VanEtten, et al., 1989, "Phytoalexin detoxification: importance for  
pathogenicity and practical implications," *An Rev Phytopathology* 27: 143-164).

30 Isoflavonoids also function in plant-microbe interactions in the establishment  
of bacterial or fungal symbioses with plants. Isoflavonoids have been reported to  
20 regulate bacterial nodulation genes, acting as a major *nod* gene inducer (Kosslak, et  
al., 1987, "Induction of *Bradyrhizobium japonicum* common *nod* genes by  
35 isoflavones isolated from *Glycine max*," *Proc Natl Acad Sci USA* 84: 7428-7432)  
and/or transcription activator (Dakora, et al., 1993, "Common bean root exudates  
contain elevated levels of daidzein and coumestrol in response to *Rhizobium*  
40 25 inoculation," *Mol Plant-Microbe Interact* 6: 665-668). Isoflavonoids have also been  
shown to have a role on the establishment of the symbiotic vesicular arbuscular  
mycorrhizal (VAM) association of the fungus *Glomus* with legume roots. (Kape, et  
45 al., 1992, "Legume root metabolites and VA-mycorrhiza development," *J Plant*  
*Physiol* 141: 54-60). Xie et al have reported that the isoflavonoids coumestrol,  
30 daidzein and genistein have small but significant stimulatory effects on the degree of  
mycorrhizal colonization of soybean, and that one effect of isoflavonoids on the

soybean mycorrhizal symbiosis could be via induction of nodulation factors from co-colonizing Rhizobia, since nod-factors have also been shown to stimulate fungal colonization (Xie, et al., 1995, "Rhizobial nodulation factors stimulate mycorrhizal colonization of nodulating and nonnodulating soybeans," *Plant Physiology* 108: 1519-1525).

In addition to the advantages that the presence of isoflavonoids confers to plants, a significant body of evidence indicates that dietary consumption of isoflavonoids can provide benefits to human health. Dietary isoflavones have been ascribed strong cancer chemopreventative activity in humans, and display a range of pharmacological activities suggestive of various other health promoting effects, including phytoestrogen activity as both estrogenic and anti-estrogenic agents (Coward, et al., 1993, "Genistein, daidzein, and their -glycoside conjugates: antitumor isoflavones in soybean foods from American and Asian diets," *J Agricultural and Food Chemistry* 41: 1961-1967; Martin, et al., 1996, "Interactions between phytoestrogens and human sex steroid binding protein," *Life Sciences* 58: 429-436); anticancer effects associated with phytoestrogenic activity (Lee, et al., 1991, "Dietary effects on breast-cancer risk in Singapore," *Lancet* 337: 1197-1200; Adlercreutz, et al., 1991, "Urinary excretion of lignans and isoflavonoid phytoestrogens in Japanese men and women consuming a traditional Japanese diet," *Am J Clin Nutr* 54: 1093-1100); anticancer effects associated with inhibition of several enzymes including DNA topoisomerase and tyrosine protein kinase (Akiyama, et al., 1987, "Genistein, a specific inhibitor of tyrosine-specific protein kinases," *J Biol Chem* 262: 5592-5599; Uckun, et al., 1995, "Biotherapy of B-cell precursor leukemia by targeting genistein to CD19-associated tyrosine kinases," *Science* 267: 886-891); suppression of alcohol consumption (Keung, W. M. and B. L. Vallee, 1993, "Daidzin: A potent, selective inhibitor of human mitochondrial aldehyde dehydrogenase," *Proc Natl Acad Sci USA* 90: 1247-1251; Keung, et al., 1995, "Daidzin suppresses ethanol consumption by Syrian golden hamsters without blocking acetaldehyde metabolism," *Proc Natl Acad Sci USA* 92: 8990-8993); antioxidant activity (Arora, et al., 1998, "Antioxidant activities of isoflavones and their biological metabolites in a liposomal system," *Arch Biochem Biophys* 356: 133-141; Tikkanen, et

5 al., 1998, "Effect of soybean phytoestrogen intake on low density lipoprotein  
oxidation resistance," *Proc Natl Acad Sci USA* 95: 3106-3110); effects on calcium  
metabolism, some of which may be linked to protective effects against osteoporosis  
10 (Tomonaga, et al., 1992, "Isoflavonoids, genistein, PSI-tectorigenin, and orobol,  
5 increase cytoplasmic free calcium in isolated rat hepatocytes," *Biochem Biophys Res  
Com* 182: 894-899; Draper, et al., 1997, "Phytoestrogens reduce bone loss and bone  
resorption in oophorectomized rats," *J Nutr* 127: 1795-1799); and cardiovascular  
15 effects (Wagner, et al., 1997, "Dietary soy protein and estrogen replacement therapy  
improve cardiovascular risk factors and decrease aortic cholesteryl ester content in  
10 ovariectomized cynomolgus monkeys," *Metabolism - Clinical and Experimental* 46:  
698-705).

20 At present, the only dietary sources of isoflavonoids for humans are certain  
legumes such as soybean or chickpea. The development of methods to genetically  
25 manipulate isoflavonoids in plants, either to widen the source of dietary isoflavonoids  
15 for humans, or to exploit the biological activities of isoflavonoids for plant protection  
and improvement, is wholly dependent on the availability of cloned genes encoding  
the various enzymes of isoflavonoid biosynthesis. Of these, the isoflavone synthase  
30 (IFS) complex constitutes the first committed reactions, and as such represents the  
means to introduce isoflavonoids into plants that do not possess the pathway.

20 In 1984, Hagmann and Grisebach provided the first evidence for the enzymatic  
conversion of flavanone to isoflavone (the IFS reaction) in a cell free system  
35 (Hagmann, M. and H. Grisebach, 1984, "Enzymatic rearrangement of flavanone to  
isoflavone," *FEBS Letters* 175: 199-202). They demonstrated that microsomes from  
elicitor-treated soybean cell suspension cultures could catalyze the conversion of 2(S)-  
40 naringenin to genistein, or of 2(S)-liquiritigenin to daidzein, in the presence of  
25 NADPH. The crude microsomal enzyme preparation, which was stable at -70°C but  
had a half-life of only 10 minutes at room temperature, was absolutely dependent on  
NADPH and molecular oxygen. It was subsequently shown that the reaction  
45 proceeded in two steps. The flavanone was converted in a cytochrome P450-catalyzed  
30 reaction requiring NADPH and O<sub>2</sub> to the corresponding 2-hydroxyisoflavanone. This



5 relatively unstable compound, which could, however, be identified by mass  
spectrometric analysis, then underwent dehydration to yield the isoflavone. The  
dehydration reaction appeared to be catalyzed by an enzyme present predominantly in  
10 the cytoplasmic supernatant, although it was not possible to remove all this activity  
5 from the microsomes. The corresponding 2-hydroxyisoflavanone spontaneously  
converted to genistein, for example, in methanol at room temperature. Kinetic  
analysis indicated that the 2-hydroxyisoflavanone was formed prior to genistein,  
15 consistent with its being an intermediate in isoflavone formation. (Kochs, G. and H.  
Grisebach, 1986, "Enzymic synthesis of isoflavones," *European J Biochem* 155: 311-  
10 318).

20 Involvement of cytochrome P450 in the 2-hydroxyisoflavanone synthase  
reaction was confirmed by inhibition by CO, replacing O<sub>2</sub> with N<sub>2</sub>, and examining the  
effects of a range of known P450 inhibitors of which ancyimidol was the most  
25 effective. The enzyme co-migrated with the endoplasmic reticulum markers  
15 cinnamate 4-hydroxylase (another cytochrome P450) and cytochrome b5 reductase on  
Percoll gradients. The enzyme is stereoselective, and (2R)-naringenin is not a  
substrate. (Kochs, G. and H. Grisebach, 1986, "Enzymic synthesis of isoflavones,"  
30 *European J Biochem* 155: 311-318).

20 The origin of the 2-hydroxyl group was determined from studies on the IFS  
present in microsomes from elicited cell cultures of *Pueraria lobata*. <sup>18</sup>O from <sup>18</sup>O<sub>2</sub>  
35 was incorporated into the 2-hydroxyl group, resulting in a 2-hydroxyisoflavanone with  
molecular ion shifted by two mass units, whereas there was no corresponding shift in  
the molecular ion of daidzein, consistent with the subsequent dehydration reaction  
40 (Hashim, et al., 1990, "Reaction mechanism of oxidative rearrangement of flavanone  
25 in isoflavone biosynthesis," *FEBS Letters* 271: 219-222). The currently accepted  
model for the reaction pathway of IFS as illustrated in Fig. 1, therefore, involves  
P450-catalyzed hydroxylation coupled to aryl migration, a reaction with mechanistic  
45 similarities to the well described proton migration mechanism of some P450 reactions  
(Hakamatsuka, et al., 1991, "P-450-dependent oxidative rearrangement in isoflavone

5 biosynthesis: reconstitution of P-450 and NADPH:P450 reductase," *Tetrahedron* 47:  
5969-5978).

10 Currently, there have been no reports on purification to homogeneity or  
molecular cloning of the cytochrome P450 of the IFS complex because of the extreme  
5 lability of the enzyme. The 2-hydroxyisoflavanone synthase cytochrome P450 from  
*Pueraria* has been solubilized with Triton X-100, and partially purified by DEAE-  
15 Sepharose chromatography; the enzymatic reaction could be reconstituted by addition  
of NADPH cytochrome P450 reductase that separated from the hydroxylase on the ion  
exchange column (Hakamatsuka, et al., 1991, *Tetrahedron* 47: 5969-5978). A 2-  
20 hydroxyisoflavanone dehydratase has been purified from elicitor-treated *P. lobata*  
cells, and has been shown to be a soluble monomeric enzyme of subunit Mr 38,000  
(Hakamatsuka, et al., 1998, "Purification of 2-hydroxyisoflavanone dehydratase from  
the cell cultures of *Pueraria lobata*," *Phytochemistry* 49: 497-505). It is not yet clear  
25 whether this enzyme physically associates with the P450 hydroxylase catalyzing the  
15 aryl migration, or even whether this activity is essential for isoflavone formation *in*  
*planta* in view of the spontaneous conversion of 2-hydroxyisoflavanone to isoflavone.

30 Flavanone is a potential substrate for more than one type of hydroxylation  
reaction at the 2-position. Thus, elicitor-treated cell cultures of alfalfa and  
*Glycyrrhiza echinata* have been shown to accumulate the dibenzoylmethane licodione  
20 (Kirikae, et al., 1993, "Biosynthesis of a dibenzoylmethane, licodione, in cultured  
alfalfa cells induced by yeast extract," *Biosci Biotech Biochem* 57: 1353-1354).  
35 Licodione synthase is, by classical criteria, a cytochrome P450, the activity of which is  
induced by yeast elicitor in *Glycyrrhiza* cells (Otani, et al., 1994, "Licodione synthase,  
a cytochrome P450 monooxygenase catalyzing 2-hydroxylation of 5-deoxyflavanone,  
40 25 in cultured *Glycyrrhiza echinata* L. cells," *Plant Physiol* 105: 1427-1432). The  
reaction it catalyzes involves 2-hydroxylation of flavanone followed by hemiacetal  
opening instead of aryl migration, and the reaction was thought to have mechanistic  
45 similarities to the flavone synthase II enzyme previously characterized from soybean  
(Kochs, G. and H. Grisebach, 1987, "Induction and characterization of a NADPH-  
30 dependent flavone synthase from cell cultures of soybean," *Z. Naturforsch* 42C: 343-

348). A gene encoding the flavone synthase II/licodione synthase from *Glycyrrhiza* has been cloned (Akashi, et al., 1998, "Identification of a cytochrome P450 cDNA encoding (2S)-flavanone 2-hydroxylase of licorice (*Glycyrrhiza echinata* L.: *Fabaceae*) which represents licodione synthase and flavone synthase II," *FEBS Letters* 431: 287-290), and a different cytochrome P450 gene encoding flavone synthase II has recently been cloned from *Gerbera hybrida* (Martens, S. and G. Forkmann, "Cloning and expression of flavone synthase II from *Gerbera* hybrids," *Plant J* 20: 611-618).

Although the reactions catalyzed by IFS are critical for the formation of all isoflavonoids in plants, there have been no previous reports of the isolation of genes encoding components of isoflavone synthase, although genes encoding most of the other enzymes of the isoflavonoid pathway, including downstream enzymes converting simple isoflavones to antimicrobial phytoalexins, have been characterized (Dixon, et al., 1995, "The isoflavonoid phytoalexin pathway: from enzymes to genes to transcription factors," *Physiologia Plantarum* 93: 385-392). Thus, the unavailability of isoflavone synthase genes has made it heretofore impossible to utilize the downstream genes for regulating isoflavonoid concentrations in legumes and other plants that do have the isoflavonoid pathway, or for engineering antimicrobial and pharmacologically active isoflavonoids in transgenic plants of species that do not have the isoflavonoid pathway.

Genes encoding the enzyme catalyzing the first step of the isoflavone synthase reaction have now been isolated and purified from soybean and *Medicago truncatula* (barrel medic).

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 depicts the currently accepted model for the reaction pathway of IFS wherein the flavanone is converted in a cytochrome P450-catalyzed reaction requiring NADPH and O<sub>2</sub> to the corresponding 2-hydroxyisoflavanone which then undergoes dehydration to yield the isoflavone.

Fig. 2 depicts the nucleotide sequence of soybean CYP93C1v2.

Fig. 3 depicts the amino acid sequence of soybean CYP93C1v2 compared to licorice CYP93B1.

Fig. 4 depicts the nucleotide sequence of *Medicago truncatula* mtIFSE3.

Fig. 5 depicts the amino acid sequence of *Medicago truncatula* mtIFSE3 compared to soybean CYP93C1v2.

Fig. 6A and Fig. 6B depict HPLC traces of extracts from pooled tissues (leaves, shoots, flowers) of *Arabidopsis thaliana* ecotype Columbia harboring an empty tDNA vector (Fig. 6A) and *Arabidopsis thaliana* ecotype Columbia harboring the soybean CYP93C1v2 cDNA sequence (Fig. 6B). The empty vector transformed line contains a number of flavonol glycosides and other phenolic compounds that are also present in the CYP93C1v2 transformed line. These compounds were identified as (a) rhamnose (Rha)- glucose (Glc)- quercetin (Q), (b) uncharacterized conjugate of Q, (c) Rha-Glc-Rha-Kaempferol (K), (d) Glu-Rha-Q, (e) Rha-Rha-Q, (f) Glc-Rha-K, (g) sinapic acid, (h) Rha-Rha-K. Three additional compounds were observed in the CYP93C1v2 transformed line (Fig. 6B), and labeled "1," "2" and "3." Fig. 6C depicts a total ion chromatogram of partially purified peaks 2 and 3, and the insets show the specific ions generated from these compounds. Peak 2 has a parental molecular mass ion of 579.5 consistent with genistein conjugated to a glucose-rhamnose disaccharide, and two further mass ions of 417.5 and 271.3, representing Rha-genistein and free genistein, respectively. Peak 3, which has a parental molecular ion of mass 417.5, is thereby identified as Rha-genistein.

Fig. 7A and Fig. 7B depict HPLC traces of the same extracts as shown in Fig. 6A (empty-vector transformed) and Fig. 6B, (CYP93C1v2 transformed), but following digestion with  $\beta$ -glucosidase. Peaks 2 and 3 remained at the same retention time as in Fig. 6A and 6B. However, Peak 1 disappeared, and was replaced with a new Peak 4 of much later retention time. Fig. 7C shows the total ion chromatograph of purified Peak 4, and the inset shows the parental molecular ion, with mass of 271.2, consistent with Peak 4 being free genistein. Fig. 7D shows a total ion chromatograph, and the parental molecular ion, of an authentic sample of genistein.

5 Fig. 8A, 8B, 8C and 8D are high performance liquid chromatography (HPLC)  
chromatograms depicting the presence of new peaks at RT 29.96 and 37.7 min  
representing the presence of the isoflavone daidzein formed from the flavanone  
10 liquiritigenin, or the isoflavone genistein formed from the flavanone naringenin, in  
5 insect cell microsomes expressing CYP93C1v2. Fig. 8A depicts the presence of  
NADPH during incubation with liquiritigenin. Fig. 8B depicts the absence of NADPH  
during incubation with liquiritigenin. Fig. 8C depicts the presence of NADPH during  
15 incubation with naringenin. Fig. 8D depicts the lack of a reaction when soybean  
CYP93E expressed in insect cells is incubated with liquiritigenin in the presence of  
10 NADPH.

20 Fig. 9A and Fig. 9B are mass spectra of BSTFA (*N,O*-bis(trimethylsilyl)  
trifluoroacetamide) derivatives. Fig. 9A depicts the mass spectrum of the BSTFA  
derivative of the product of the reaction catalyzed by CYP93C1v2 in insect cells using  
25 liquiritigenin as substrate, and Fig. 9B shows the mass spectrum of the BSTFA  
15 derivative of an authentic sample of daidzein.

#### 30 SUMMARY OF THE INVENTION

In one aspect, the invention is a method for introducing into a naturally non-  
isoflavonoid-producing plant species the enzyme catalyzing the aryl migration of a  
flavanone to form an isoflavanone intermediate or an isoflavone, comprising  
35 20 introducing a DNA segment encoding the enzyme into the plant to form a transgenic  
plant, wherein the transgenic plant expresses the DNA segment under the control of a  
suitable constitutive or inducible promoter when the transgenic plant is exposed to  
conditions which permit expression. The DNA segment can comprise isolated  
40 genomic DNA or recombinant DNA. Preferably, the DNA segment is a CYP93C  
25 gene. An exemplary DNA segment from a soybean CYP93C gene consists essentially  
of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence  
depicted in SEQ ID NO:1. Another preferred DNA segment comprises a *Medicago*  
45 *truncatula* homolog of a CYP93C gene, more preferably, the sequence from about  
nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.  
30 Plants transformed by this method may also preferably express chalcone synthase,

5 chalcone reductase, and chalcone isomerase genes to cause in vivo formation of  
daidzein or a daidzein derivative, and the chalcone synthase, chalcone reductase, and  
10 chalcone isomerase genes may also be transgenes. Plants transformed by this method  
may also preferably further comprise downstream genes, for example, isoflavone *O*-  
5 methyltransferase, isoflavone 2'-hydroxylase, isoflavone reductase, and vestitone  
reductase, to metabolize a formed isoflavone to biologically active isoflavonoid  
derivatives or conjugates. The plant can comprise isoflavone 4'-*O*-methyl-transferase  
15 to cause formation of biochanin A or a biochanin A derivative from the isoflavanone  
intermediate. An exemplary flavanone substrate for this transformation method is  
20 liquiritigenin and/or naringenin.

20 In another aspect, the present invention is a method for increasing the level of  
isoflavonoid compounds in naturally isoflavonoid-producing plants comprising  
introducing a DNA segment encoding the enzyme catalyzing the aryl migration of a  
25 flavanone to yield an isoflavonoid to form a transgenic plant, wherein the transgenic  
15 plant expresses the DNA segment under the control of a suitable constitutive or  
inducible promoter when the transgenic plant is exposed to conditions which permit  
expression. With this method, the resulting isoflavonoid can be an isoflavanone  
30 intermediate, an isoflavone, an isoflavone derivative, and an isoflavone conjugate.  
The DNA segment can comprise isolated genomic DNA or recombinant DNA.  
20 Preferably, the DNA segment is a CYP93C gene. An exemplary DNA segment from  
a soybean CYP93C gene consists essentially of the sequence from about nucleotide 36  
35 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1. Another  
preferred DNA segment comprises a *Medicago truncatula* homolog of a CYP93C  
gene, more preferably, the sequence from about nucleotide 92 to about nucleotide  
40 25 1657 of the sequence depicted in SEQ ID NO:4. An exemplary flavanone substrate  
for this transformation method is liquiritigenin and/or naringenin.

45 In another aspect, the invention is a method for synthesizing an isoflavanone  
intermediate or an isoflavone from a flavanone by expressing a recombinant CYP93C  
gene segment in a suitable bacterial, fungal, algal, or insect cell system. An  
30 exemplary gene segment consists essentially of the sequence from about nucleotide 36

5 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1. Another  
exemplary gene segment consists essentially of the sequence from about nucleotide 92  
to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

10 In another aspect, the invention is a method of reducing the levels of  
5 isoflavonoid compounds in a naturally isoflavonoid-producing plant comprising  
introducing and expressing an antisense or gene silencing construct that contains an  
15 intact CYP93C gene or segments thereof into the plant. An exemplary gene consists  
essentially of the sequence from about nucleotide 36 to about nucleotide 1598 of the  
sequence depicted in SEQ ID NO:1. Another exemplary gene consists essentially of  
10 the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence  
depicted in SEQ ID NO:4.

25 In another aspect, the invention is a naturally non-isoflavonoid-producing plant  
cell transformed by introducing a DNA segment encoding the enzyme catalyzing the  
aryl migration of a flavanone to form an isoflavanone intermediate or an isoflavone,  
15 wherein the transformed plant cell expresses the DNA segment under the control of a  
suitable constitutive or inducible promoter when exposed to conditions which permit  
expression. The DNA segment can comprise isolated genomic DNA or recombinant  
30 DNA. Preferably, the DNA segment is a CYP93C gene. An exemplary DNA  
segment from a soybean CYP93C gene consists essentially of the sequence from about  
20 nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1.  
35 Another preferred DNA segment comprises a *Medicago truncatula* homolog of a  
CYP93C gene, more preferably, the sequence from about nucleotide 92 to about  
nucleotide 1657 of the sequence depicted in SEQ ID NO:4. Plants transformed by this  
40 method may also preferably express chalcone synthase, chalcone reductase, and  
25 chalcone isomerase genes to cause in vivo formation of daidzein or a daidzein  
derivative, and the chalcone synthase, chalcone reductase, and chalcone isomerase  
genes may also be transgenes. Plants transformed by this method may also preferably  
45 further comprise downstream genes, for example, isoflavone *O*-methyltransferase,  
isoflavone 2'-hydroxylase, isoflavone reductase, and vestitone reductase, to  
30 metabolize a formed isoflavanone intermediate to biologically active isoflavonoid

5 derivatives or conjugates. The plant can comprise isoflavone 4'-O-methyl-transferase to cause formation of biochanin A or a biochanin A derivative from the isoflavanone intermediate.

10 In another aspect, the invention is a naturally isoflavonoid-producing plant cell  
5 transformed by introducing a DNA segment encoding the enzyme catalyzing the aryl migration of a flavanone to yield an isoflavonoid to form a transformed plant cell, wherein the transformed plant cell expresses the DNA segment under the control of a  
15 suitable constitutive or inducible promoter when exposed to conditions which permit expression. With this method, the resulting isoflavonoid can be an isoflavanone intermediate, an isoflavone, an isoflavone derivative, and an isoflavone conjugate.  
20 The DNA segment can comprise isolated genomic DNA or recombinant DNA. Preferably, the DNA segment is a CYP93C gene. An exemplary DNA segment from a soybean CYP93C gene consists essentially of the sequence from about nucleotide 36  
25 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1. Another preferred DNA segment comprises a *Medicago truncatula* homolog of a CYP93C  
15 gene, more preferably, the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

30 In another aspect, the invention is a transgenic plant cell having reduced levels of isoflavonoid compounds, the plant cell transformed by introducing an antisense or  
20 gene silencing construct that contains an intact CYP93C gene or segments thereof into the plant cell. An exemplary gene consists essentially of the sequence from about  
35 nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1. Another exemplary gene consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

25 In another aspect, the invention is an isolated gene or DNA segment comprising a portion which encodes a cytochrome P450 that can catalyze the aryl  
45 migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the portion consists essentially of about nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1. An exemplary gene is the soybean  
30 gene encoding the enzyme catalyzing the aryl migration of liquiritigenin. Another



5 exemplary gene is the soybean gene encoding the enzyme catalyzing the aryl  
migration of naringenin.

10 In another aspect, the invention is a protein encoded by a portion of an isolated  
gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl  
5 migration of a flavanone to yield an isoflavanone intermediate or an isoflavone,  
wherein the portion consists essentially of about nucleotide 36 to about nucleotide  
15 1598 of the sequence depicted in SEQ ID NO:1.

20 In another aspect, the invention is an isolated gene or DNA segment  
comprising a portion which encodes a cytochrome P450 that can catalyze the aryl  
10 migration of a flavanone to yield an isoflavanone intermediate or an isoflavone,  
wherein the portion is a *Medicago truncatula* homolog of a CYP93C gene. An  
exemplary gene or DNA segment consists essentially of about nucleotide 92 to about  
25 nucleotide 1657 of the sequence depicted in SEQ ID NO:4. An exemplary gene is the  
*Medicago truncatula* gene encoding the enzyme catalyzing the aryl migration of  
15 liquiritigenin. Another exemplary gene is the *Medicago truncatula* gene encoding the  
enzyme catalyzing the aryl migration of naringenin.

30 In another aspect, the invention is a protein encoded by a portion of an isolated  
gene or a DNA segment which encodes a cytochrome P450 that can catalyze the aryl  
migration of a flavanone to yield an isoflavanone intermediate or an isoflavone,  
35 20 wherein the portion is a *Medicago truncatula* homolog of a CYP93C gene.

40 In yet another aspect, the invention is a food comprising edible transgenic plant  
material capable of being ingested for its nutritional value, wherein the transgenic  
plant has been transformed with an isolated gene or DNA segment which encodes a  
cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an  
25 isoflavanone intermediate or an isoflavone, and wherein the transgenic plant exhibits  
increased levels of an isoflavonoid when compared to the level of the isoflavonoid in  
45 plants of the same species which do not comprise the isolated gene or DNA segment.

50 In yet another aspect, the invention is a food comprising at least one  
isoflavonoid, wherein the isoflavonoid is isolated from a transgenic plant transformed

5 with an isolated gene or DNA segment which encodes a cytochrome P450 that can  
catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an  
isoflavone, and wherein the transgenic plant exhibits increased levels of an  
10 isoflavonoid when compared to the level of the isoflavonoid in plants of the same  
5 species which do not comprise the isolated gene or DNA segment.

15 In yet another aspect, the invention is a composition comprising at least a  
portion of a transgenic plant transformed with an isolated gene or DNA segment  
which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone  
to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant  
20 10 exhibits increased levels of an isoflavonoid when compared to the level of the  
isoflavonoid in plants of the same species which do not comprise the isolated gene or  
DNA segment, and wherein the composition is suitable for ingestion as a food stuff, a  
nutritional supplement, an animal feed supplement, or a nutraceutical.

25 In yet another aspect, the invention is a composition comprising an  
15 isoflavonoid suitable for administration as a food stuff, a nutritional supplement, an  
animal feed supplement, a nutraceutical, or a pharmaceutical, wherein the isoflavonoid  
is isolated from at least a portion of a transgenic plant transformed with an isolated  
30 gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl  
migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, and  
20 wherein the transgenic plant exhibits increased levels of an isoflavonoid when  
35 compared to the level of the isoflavonoid in plants of the same species which do not  
comprise the isolated gene or DNA segment.

40 In yet another aspect, the invention is a method of increasing the nutritional  
value of a plant by transforming the plant with an isolated gene or DNA segment  
25 which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone  
to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant  
45 exhibits increased levels of an isoflavonoid when compared to the level of the  
isoflavonoid in plants of the same species which do not comprise the isolated gene or  
DNA segment.

5 In yet another aspect, the invention is a method of using a transgenic plant transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone  
10 intermediate or an isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of the isoflavonoid in plants of the  
5 same species which do not comprise the isolated gene or DNA segment, to provide a nutraceutical benefit to a human or animal administered the isoflavonoid. The  
15 isoflavonoid can be administered by ingestion of at least a portion of the plant. The isoflavonoid can also be administered by ingestion of a composition comprising an  
10 isoflavonoid isolated from the plant.

20 In yet another aspect, the invention is a method of using an isoflavonoid isolated from a transgenic plant transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone  
25 to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of the  
15 isoflavonoid in plants of the same species which do not comprise the isolated gene or DNA segment, to provide a pharmaceutical benefit to a patient administered the  
30 isoflavonoid.

20 In yet another aspect, the invention is a method of increasing disease resistance in a plant by transforming the plant with an isolated gene or DNA segment which  
35 encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant exhibits an  
40 increased level of an isoflavonoid when compared to the level of the isoflavonoid in plants of the same species which do not comprise the isolated gene or DNA segment.

25 In yet another aspect, the invention is a method of increasing nodulation efficiency of a leguminous plant by transforming the plant with an isolated gene or  
45 DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the  
transgenic plant exhibits an increased level of an isoflavonoid released from the roots

5 when compared to the level of the isoflavonoid released from the roots of plants of the same species which do not comprise the isolated gene or DNA segment.

10 In yet another aspect, the invention is a transgenic leguminous plant exhibiting increased nodulation efficiency transformed with an isolated gene or DNA segment  
5 which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid released from the roots when compared to the level of the isoflavonoid released from the roots of plants of the same species which do not comprise the isolated gene or DNA segment.

20 In yet another aspect, the invention is a method of increasing bacterial or fungal symbiosis in a plant by transforming the plant with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the  
25 transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of the isoflavonoid in plants of the same species which do not comprise the isolated gene or DNA segment.

30 In yet another aspect, the invention is a transgenic plant exhibiting increased bacterial or fungal symbiosis transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant  
35 20 exhibits an increased level of an isoflavonoid when compared to the level of the isoflavonoid in plants of the same species which do not comprise the isolated gene or DNA segment.

40 In yet another aspect, the invention is a transgenic plant comprising at least one recombinant DNA sequence encoding a cytochrome P450 that can catalyze the aryl  
25 migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of the isoflavonoid in plants of the same species which do not comprise the recombinant DNA sequence.

5 In yet another aspect, the invention is seed from a transgenic plant comprising  
at least one recombinant DNA sequence encoding a cytochrome P450 that can  
catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an  
10 isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid  
5 when compared to the level of the isoflavonoid in plants of the same species which do  
not comprise the recombinant DNA sequence.

15 In yet another aspect, the invention is progeny from a transgenic plant  
comprising at least one recombinant DNA sequence encoding a cytochrome P450 that  
can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or  
10 an isoflavone, wherein the transgenic plant exhibits an increased level of an  
20 isoflavonoid when compared to the level of the isoflavonoid in plants of the same  
species which do not comprise the recombinant DNA sequence.

25 In yet another aspect, the invention is progeny from seed of a transgenic plant  
comprising at least one recombinant DNA sequence encoding a cytochrome P450 that  
15 can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or  
an isoflavone, wherein the transgenic plant exhibits an increased level of an  
30 isoflavonoid when compared to the level of the isoflavonoid in plants of the same  
species which do not comprise the recombinant DNA sequence.

35 In yet another aspect, the invention is use of a transgenic plant transformed  
20 with an isolated gene or DNA segment which encodes a cytochrome P450 that can  
catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an  
isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid  
when compared to the level of the isoflavonoid in plants of the same species which do  
40 not comprise the isolated gene or DNA segment, for the preparation of a nutraceutical  
25 preparation for achieving a nutritional effect.

45 In yet another aspect, the invention is use of a transgenic plant transformed  
with an isolated gene or DNA segment which encodes a cytochrome P450 that can  
catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an  
isoflavone, wherein the transgenic plant exhibits an increased level of an isoflavonoid

when compared to the level of the isoflavonoid in plants of the same species which do not comprise the isolated gene or DNA segment, for the preparation of a pharmaceutical preparation for achieving a therapeutic effect.

#### DETAILED DESCRIPTION

One aspect of the present invention is an isolated gene which encodes the first step of the isoflavone synthase reaction: a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavone. Genes and corresponding cDNA of the soybean or *Medicago truncatula* CYP93 family have been isolated. The enzymes encoded by the genes of the present invention are isoflavone synthases (IFS) and can catalyze the aryl migration of a flavanone to yield an isoflavone either directly or through the intermediacy of a 2-hydroxyisoflavanone. One isolated soybean gene is classified as *CYP93C1v2*.

Cytochrome P450 enzymes belong to a large superfamily of enzymes that are abundant in every living organism. The P450 nomenclature committee has determined that each P450 should carry a "CYP" designation and arbitrarily divided the superfamily into families (alphabetical designation), subfamilies (numerical designation) and allelic variants ("v" plus numerical designation) based on amino acid identity of >40%, >55%, and >97%, respectively (Nelson, et al. 1993. "The P450 superfamily update on new sequences, gene mapping, accession numbers, early trivial names of enzymes, and nomenclature," *DNA Cell Biol* 12:1). Thus, *CYP93C1v2* is a variant of the first described P450 belonging to the third subfamily (C) of the ninety-third P450 family.

Utilizing the procedures presented herein, any plant known to produce isoflavonoids may also serve as sources of suitable DNA, or coding sequences may be synthesized in vitro based on the sequences for the IFS genes of the present invention. CYP93 family members can also be obtained from other plant species by polymerase chain reaction amplification methods known to those skilled in the art, using primer sequences corresponding to regions of nucleotide conservation between CYP93 family members. Furthermore, the genes of the present invention are defined by their

5 catalytic activity: the aryl migration of a flavanone to yield an isoflavone. The gene  
sequences presented as SEQ ID NO:1 and SEQ ID NO:4 are exemplary, and it is  
understood that modifications to these genes which do not alter the catalytic activity of  
10 its encoded protein fall within the scope of the present invention. While a preferred  
5 IFS gene contains the entire open reading frame, portions of or the entire 5' and 3'  
untranslated regions as well as portions of the vector sequence can also be present.  
With the isolation and functional identification of these isoflavone synthase (IFS)  
15 genes that encode the first key step in isoflavone formation, the aryl migration  
reaction, it is now possible to introduce the isoflavonoid pathway into all plant species,  
10 including those that do not naturally possess this pathway.

20 Another aspect of the present invention is a genetically modified plant which  
has been transformed with a gene of the present invention. For example, when the  
*CYP93C1v2* gene is transferred into the model plant *Arabidopsis thaliana*, which does  
25 not naturally produce isoflavonoids, the isoflavone genistein accumulates as a series of  
15 glycoconjugates (Example 1). This demonstrates that the genes of the present  
invention can be genetically engineered into plants which do not naturally contain the  
isoflavonoid pathway, and the transgenic plants can then produce isoflavonoids,  
30 resulting in plants with improved disease resistance and/or value added health benefits  
for humans. In the present invention, unless otherwise stated, as used herein, the term  
20 "plant" or "progeny" includes plant parts, plant tissue, plant cells, plant protoplasts,  
plant cell tissue cultures from which plants can be regenerated, plant calli, plant  
35 clumps, explants, plant cells that are intact in plants, or parts of plants, such as  
embryos, pollen, ovules, flowers, capsules, stems, leaves, seeds, roots, root tips, and  
the like. Furthermore, the present invention includes the IFS genes expressed in  
40 25 various parts of the plant, e.g., in aerial portions of the plant useful for increasing  
disease resistance or production of health promoting isoflavonoid nutraceuticals, in  
seeds useful for increasing levels of isoflavones and their conjugates, or in roots useful  
45 for increasing disease resistance or production of nodulation gene inducing  
isoflavones.

5 In another aspect, the present invention is a method of improving disease  
resistance and a transgenic plant with increased disease resistance. By transforming a  
plant which does not naturally make isoflavones with an IFS gene of the present  
10 invention, disease resistance can be genetically engineered into the plant by providing  
5 the necessary enzyme to convert its natural flavanones into isoflavonoids. The  
introduction and subsequent expression of an IFS gene of the present invention into a  
crop species which naturally possesses the isoflavonoid pathway results in increased  
15 levels of the isoflavonoid defense compounds.

10 In another aspect, the present invention is a method of increasing levels of  
isoflavonoids that might be beneficial to the establishment of bacterial or fungal  
20 symbioses with plants and a transgenic plant with an increased capacity for symbiotic  
association with bacteria or fungi. Bacterial nodulation can be stimulated in  
transgenic leguminous plants by expression of an IFS gene of the present invention  
25 and decreased by expression of antisense constructs or constructs designed to promote  
15 gene silencing that contain an intact IFS gene or segments thereof. Mycorrhizal  
colonization of leguminous plants can also be increased through the introduction and  
expression of an IFS gene of the present invention.

30 In yet another aspect, the present invention is a method of producing  
isoflavonoid compounds in plants or any other organism to be used in nutraceuticals or  
20 pharmaceuticals to confer human or animal health benefits. Edible transgenic plants  
high in isoflavonoids can be utilized as food for humans and animals. Edible  
35 compositions high in isoflavonoids can also be made by incorporation of the  
transgenic plants or plant materials, or by incorporation of isoflavonoids isolated from  
the transgenic plants. Compositions useful for administration as a food stuff, a  
40 nutritional supplement, an animal feed supplement, a nutraceutical, or a  
25 pharmaceutical can be made by incorporation of the transgenic plants or plant  
materials, or by incorporation of isoflavonoids isolated from the transgenic plants.  
45 The nutritional value of a plant can be increased by transforming the plant with an IFS  
gene of the present invention and, as a result, accumulating high amounts of  
30 isoflavonoids in the plant.



5 The soybean IFS gene of the present invention was isolated and purified according to the detailed procedures outlined in Example 2. The DNA sequence is shown in SEQ ID NO:1 and Fig. 2, and the encoded protein sequence of the isolated soybean CYP93C clone is shown in SEQ ID NO:2 and Fig. 3. For comparison, Fig. 3 also shows the protein sequence alignment between the isolated CYP93C clone (SEQ ID NO:2) and CYP93B1 (SEQ ID NO:3), the licorice licodione synthase.

15 The DNA and protein sequences of the soybean CYP93C1 open reading frame were deposited in the Genbank data base under accession # AF022462. The deposition was made by Siminszky, Dewey and Corbin, and the sequence described as representing a gene induced in soybean in response to herbicide safeners. However, 20 the function of the gene was not known and there was no understanding that it could be involved in isoflavonoid biosynthesis at the time the deposit was made (Siminszky, B., Corbin, F.T., Ward, E.R., Fleischmann, T.J. and Dewey, R.E., 1999, "Expression of a soybean cytochrome P450 monooxygenase cDNA in yeast and tobacco enhances 25 the metabolism of phenylurea herbicides." *Proc. Natl. Acad. Sci. USA* 96: 1750-1755). The sequence of the clone characterized herein differs from CYP93C1 in three nucleotide substitutions in the open reading frame that change proline 140 to leucine, 30 threonine 156 to isoleucine, and glutamate 295 to lysine. Thus, the soybean gene identified herein has been classified as CYP93C1v2.

20 The cDNA insert from CYP93C1v2 was used to probe 240,000 phage plaques from a *Medicago truncatula* root cDNA library (van Buuren, M.L., I.E. Maldonado-Mendoza, A.T. Trieu, L.A. Blaylock, and M.J. Harrison, 1999, "Novel genes induced during an arbuscular mycorrhizal (AM) symbiosis formed between *Medicago truncatula* and *Glomus versiforme*," *Mol. Plant-Microbe Interact.* 12, 171-181). Five 40 positive plaques were purified, in vivo excised, and sequenced. A full length clone designated mtIFSE3 was completely sequenced on both strands, and shown to encode the *Medicago truncatula* homolog of soybean CYP93C1. The nucleotide sequence of mtIFSE3 is shown in SEQ ID NO:4 and Fig. 4, and the protein sequence, in SEQ ID NO:5. An alignment between the protein sequences of mtIFSE3 and CYP93C1v2 is 50 shown in Fig. 5.

5 An IFS gene of the soybean or *Medicago truncatula* CYP93C subfamily or  
corresponding cDNA sequence, the open reading frame of which encodes a  
cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an  
isoflavone, either directly or through the intermediacy of a 2-hydroxyisoflavanone,  
10 can be used to introduce the isoflavonoid pathway into any plant species that does not  
naturally possess this pathway. Soybean CYP93C1v2 acts on the flavanones  
liquiritigenin to yield daidzein, and naringenin to yield genistein. Liquiritigenin is  
only formed in plants that possess the enzyme chalcone reductase (CHR) (Welle, R.  
and Grisebach, H., 1989, "Phytoalexin synthesis in soybean cells: elicitor induction of  
15 reductase involved in biosynthesis of 6'-deoxychalcone." *Arch Biochem Biophys* 272:  
97-102), and a form of chalcone isomerase that is active against 2',4,4'-  
trihydroxychalcone, the product of the co-action of chalcone synthase (CHS) with  
CHR (Dixon, R.A., Blyden, E.R., Robbins, M.P., van Tunen, A.J. and Mol, J.N.M.,  
20 1988, "Comparative biochemistry of chalcone isomerases." *Phytochemistry* 27: 2801-  
2808). Such genes are common in legumes, but not in most other plant families.  
Thus, to form daidzein in transgenic plants that do not possess the isoflavonoid  
pathway, it would be necessary to introduce three new genes, namely CHR, to co-act  
with CHS to form 2',4,4'-trihydroxychalcone, a suitable CHI to convert 2',4,4'-  
30 trihydroxychalcone to liquiritigenin, and IFS, assuming that the 2-  
hydroxyisoflavanone intermediate can spontaneously dehydrate in planta, a  
phenomenon that is demonstrated below. Without CHR present, no liquiritigenin  
would be formed, and IFS would only be able to act on naringenin to yield, assuming  
35 spontaneous dehydration of the 2-hydroxyisoflavanone, genistein.

The IFS genes of the present invention can be introduced into non-leguminous  
40 25 plants such as by standard *Agrobacterium*-based or biolistic transformation procedures  
(Horsch, et al., 1985, "A simple and general method for transferring genes into  
plants," *Science* 227:1229-1231; and Klein, et al., 1988, "Stable genetic  
transformation of intact *Nicotiana* cells by the particle bombardment process," *Proc*  
45 *Natl Acad Sci USA* 85:8502-8505). Both procedures require the construction of a  
30 plasmid vector containing a desirable transcriptional promoter driving expression of  
the gene of interest (in this case IFS), followed by a transcriptional terminator and a

5 selectable marker gene for resistance, such as to an antibiotic or a herbicide. The  
biolistic procedure coats metal particles with plasmid DNA containing the gene of  
interest and places them on a micro carrier disk. Using the biolistic apparatus, the  
10 particles are physically propelled into plant tissue. The plant tissue is then put under  
5 selection (e.g., antibiotic or herbicide) followed by regeneration. The two  
*Agrobacterium*-based procedures are "in planta" and "ex-planta", respectively. Both  
procedures require the above gene construct to be placed into a T-DNA vector, which  
15 is then transferred into *Agrobacterium tumefaciens*. The in planta procedure places the  
transformed *Agrobacterium* in the presence of plant material (flower or meristem) and  
10 the plants are allowed to seed followed by selection (e.g., antibiotic or herbicide)  
during germination. The ex-planta procedure also places *Agrobacterium* in the  
20 presence of plant material (callus, cell culture, leaf disk, hypocotyl) which is placed  
directly under selection (e.g., antibiotic or herbicide) followed by regeneration.

25 Thus, the isoflavonoid pathway can be introduced into any plant species that  
15 does not possess the enzyme catalyzing the IFS reaction by expressing the IFS gene in  
transgenic plants under the control of a suitable constitutive or inducible promoter.

30 **Example 1: Transformation of *Arabidopsis thaliana*  
with Soybean *CYP93C1V2***

Soybean CYP93C1v2 cDNA was placed in the binary plant transformation  
20 vector pCHF3, in which it is under control of the cauliflower mosaic virus 35S  
35 promoter, using standard recombinant DNA methods (Sambrook, et al. 1989.  
*Molecular Cloning. A Laboratory Manual*, 2nd Ed, Cold Spring Harbor Laboratory  
Press, New York). The gene was then transformed into plants of the crucifer,  
40 *Arabidopsis thaliana* ecotype Columbia, using *Agrobacterium tumefaciens* and a  
25 standard floral infiltration procedure (Clough, S.J. and Bent, A.F., 1998, "Floral dip: a  
simplified method for *Agrobacterium*-mediated transformation of *Arabidopsis*  
*thaliana*". *Plant J* 16: 735-743). Transgenic plants were selected by germinating the  
45 seedlings on kanamycin, and those surviving selection were allowed to set seed. T<sub>2</sub>  
seedlings expressing CYP93C1v2 were identified by standard DNA and RNA gel blot  
30 analysis (Sambrook, et al. 1989. *Molecular cloning. A Laboratory Manual*, 2nd Ed,

5 Cold Spring Harbor Laboratory Press, New York), and analyzed for accumulation of  
genistein in leaves by HPLC analysis, according to a method developed to profile the  
flavonoid components of *Arabidopsis* leaves (Graham, T.L., 1998, "Flavonoid and  
10 flavonol glycoside metabolism in *Arabidopsis*". *Plant Physiol Biochem* 36: 135-144).

5 Figure 6A shows a typical HPLC trace of a leaf extract from an untransformed  
plant. The major components are glycosides (containing glucose and rhamnose) of the  
flavonols kaempferol and quercetin. Plants harboring the soybean CYP93C1v2 gene  
15 showed an additional three peaks on HPLC analysis (Fig. 6B), indicated by the arrows  
labeled as "1," "2" and "3." No free genistein, free 2-hydroxyisoflavanone or 2-  
10 hydroxyisoflavanone conjugates were observed. However, following treatment of  
extracts with almond  $\beta$ -glucosidase (Fig 7B), one of the new peaks disappeared, and  
free genistein was now observed, consistent with the peak being a glucoside of  
20 genistein. LC-MS analysis confirmed the identities of the new compounds as a  
glucoside of genistein, glucose-rhamnose-genistein, and rhamnose-genistein (Figs. 6C  
25 and 7C and 7D, insets). Therefore, expression of CYP93C1v2 in transgenic  
*Arabidopsis* leads to formation of genistein with no requirement for an enzyme to  
catalyze the dehydration of the presumed 2-hydroxyisoflavanone intermediate.  
30 *Arabidopsis* plants then modify the genistein by exactly the same chemistry they use  
to conjugate their endogenous flavonols, namely by conjugation to glucose and  
20 rhamnose. Transgenic production of conjugates of genistein are suitable for  
nutraceutical applications, because genistein is also glycosylated in soybean, its  
35 natural dietary source (Graham, T.L., 1991, "Flavonoid and isoflavonoid distribution  
in developing soybean seedling tissues and in seed and root exudates." *Plant Physiol*  
95: 594-603).

40 25 In addition to introducing the isoflavonoid pathway into plants that do not  
possess this pathway, the level of isoflavonoid compounds can be controlled in plants  
that do possess the pathway by manipulating the level of expression of the IFS gene.  
45 Increasing the levels of isoflavonoid compounds in leguminous plants by expression  
of the IFS gene of the present invention in transgenic plants under the control of a  
30 suitable constitutive or inducible promoter can be accomplished by standard methods

5 such as *Agrobacterium*-based or biolistic transformation methods known in the art. Alternatively, the level of isoflavonoid compounds in plants can be reduced by  
10 expression of antisense constructs or constructs designed to promote gene silencing that contain an intact IFS gene, or segments thereof, in transgenic plants using  
5 methods known in the art. (Bourque, J.E., 1995, "Antisense strategies for genetic manipulations in plants," *Plant Science* 105:125-149; and Angell, S. M. and D. C. Baulcombe, 1997, "Consistent gene silencing in transgenic plants expressing a  
15 replicating potato virus X RNA," *EMBO J* 16:3675-3684). Antisense constructs for gene silencing are constructed by placing the whole or part of the cDNA in a three  
10 prime to five prime orientation behind a desirable transcriptional promoter and ahead of a transcriptional terminator in a plasmid vector. The vector may be used for  
20 biolistic transformation or the new antisense gene may be transferred to a T-DNA vector for *Agrobacterium*-based transformation. The actual mechanism of silencing by antisense constructs is unknown. Homology-dependent gene silencing or co-  
25 suppression requires the over-expression of a homologous gene; therefore, to achieve co-suppression a construct is made using a strong promoter, the gene of interest (in this case IFS) and a transcriptional terminator. The gene should be transferred to  
30 plants as described above. Gene silencing is an epigenetic phenomenon that may or may not occur with a particular gene construct. When it does occur, the inhibition of  
20 gene expression can be greater than with the antisense approach.

35 Isoflavones can be synthesized from flavanones, utilizing recombinant IFS expressed in any suitable bacterial, fungal, algal, or insect cell system. For example, naringenin is extracted in large amounts from grapefruits. A CYP93C1 enzyme can  
40 be used convert naringenin to 2,5,7,4'-tetrahydroxyisoflavanone, which spontaneously  
25 converts to the valuable nutraceutical genistein under weak acid conditions. Furthermore, daidzin can be synthesized from liquiritigenin utilizing recombinant CYP93C1 and an isoflavone glucosyltransferase (Köster, J. and W. Barz, 1981,  
45 "UDP-Glucose: isoflavone 7-O-glucosyltransferase from roots of chick pea (*Cicer arietinum* L.)." *Arch Biochem Biophys* 212: 98-104).

## Example 2: Methodology Used to Isolate and Identify IFS cDNA Clones

In an attempt to obtain cDNA clones encoding IFS, a functional genomics approach was followed. IFS activity is present in soybean seeds, which accumulate daidzein and genistein. Furthermore, IFS activity can be induced in soybean tissues in response to infection with *Phytophthora infestans*, associated with the accumulation of the isoflavonoid phytoalexin glyceollin (Bhattacharyya, M. K. and E. W. B. Ward, 1987, "Biosynthesis and metabolism of glyceollin I in soybean hypocotyls following wounding or inoculation with *Phytophthora megasperma* f. sp. *glycinea*," *Physiol Mol Plant Path* 31: 387-405). It was also known that an enzyme catalyzing a similar reaction to IFS, namely the 2-hydroxylation of flavanone but without aryl migration, belongs to the CYP93B1 subclass of cytochrome P450s (Akashi, et al, 1998, "Identification of a cytochrome P450 cDNA encoding (2S)-flavanone 2-hydroxylase of licorice (*Glycyrrhiza echinata* L.: *Fabaceae*) which represents licodione synthase and flavone synthase II," *FEBS Letters* 431: 287-290). We therefore searched an expressed sequence tag (EST) database of partial soybean sequences obtained by mass sequencing of two cDNA libraries: a *Phytophthora*-infected hypocotyl cDNA library (48 hours after infection) and a mid to late developmental stage seed library. Nine candidate P450 sequences were identified, of which three belonged to the CYP93 family. DNA probes were made from the EST clones of the three CYP93 candidates and were used to probe an RNA blot of transcripts from alfalfa suspension cells at various times after exposure to yeast elicitor, a treatment known to induce IFS activity at the onset of isoflavonoid phytoalexin accumulation (Kessmann, et al., 1990, "Stress responses in alfalfa (*Medicago sativa* L.) III. Induction of medicarpin and cytochrome P450 enzyme activities in elicitor-treated cell suspension cultures and protoplasts," *Plant Cell Reports* 9: 38-41). One P450 probe cross-hybridized and detected alfalfa transcripts that were strongly induced by elicitation. This probe was derived from a clone with high homology to soybean CYP93C1 as described below, and the insert in the EST clone was full length. The insert was excised and then cloned into the baculovirus expression system for functional identification by heterologous expression in insect cells (Pauli, H. H. and T. M. Kutchan, 1998, "Molecular cloning and functional heterologous expression of two alleles encoding (S)-N-methylcochlorine 3'-

hydroxylase (CYP80B1), a new methyl jasmonate-inducible cytochrome P-450-dependent mono-oxygenase of benzyloquinoline alkaloid biosynthesis," *The Plant J* 13: 793-801).

The carbon monoxide difference spectrum of microsomes isolated from insect cells expressing the soybean CYP93C clone indicated the presence of expressed cytochrome P450, as seen from an absorption peak at 450 nm that was not present in similar spectra from insect microsomes originating from cells transformed with a control vector. Unlabeled liquiritigenin was then fed to the microsomes in the presence of NADPH. The substrate remained unconverted in microsomes from cells harboring the control vector. However, in microsomes expressing the CYP93C clone, a new peak of RT 29.96 min was observed by high performance liquid chromatography (Fig 8A). The amount of this peak was reduced 10-fold if NADPH was omitted from the incubations (Fig. 8B). The UV spectrum of the product, obtained by diode array detection, was identical to that of authentic daidzein ( $\lambda_{\text{max}}$  248 nm, sh 302 nm,  $\lambda_{\text{min}}$  222 nm). The product was collected, derivatized, and analyzed by GC-MS. The mass spectrum of the BSTFA derivative was identical to that of an authentic sample of daidzein (Fig. 9). Microsomes containing the CYP93C clone also metabolized naringenin to yield genistein, although somewhat less efficiently than the reaction with liquiritigenin (Fig. 8C). Insect cell microsomes expressing a different soybean cytochrome P450 cDNA, CYP93E, did not convert liquiritigenin to daidzein when incubated in the presence of NADPH (Fig. 8D). These results indicate that the soybean CYP93C encodes IFS.

### Example 3: Method of Increasing Dietary Isoflavonoid Intake

Transgenic tomato plants are produced by the introduction of CYP93C1v2 via standard *Agrobacterium*-based procedures. In a preferred embodiment, the CYP93C1v2 coding sequence is under control of a gene promoter giving specific expression in the fruit. Progeny containing the coding region of the CYP93C1v2 gene are selected at the seedling stage by standard polymerase chain reaction and/or DNA blot analysis known to those skilled in the art. Plants scoring positive for possession of the transgene are grown to fruiting, and fruit analyzed for the presence of

5 isoflavones by the HPLC methods shown in Fig. 7 and Fig. 8 of the present invention. Fruit harvested from the transgenic tomato plants are ingested to increase the dietary intake of isoflavonoids.

10 It is to be understood that the above description is of preferred exemplary  
5 embodiments of the invention and is intended to be illustrative of the invention, but is not to be construed to limit the scope of the invention in any way. Modifications may be made in the structural features of the invention without departing from the scope of  
15 the invention.

In summary, isoflavones can now be genetically engineered to provide  
20 10 potential human health benefits of dietary isoflavones and to increase disease resistance in plants. Isoflavones can now be produced in transgenic plants species in which isoflavones do not naturally occur, i.e., in species other than legumes. For example, engineering constitutive production of daidzein and/or genistein or their  
25 conjugates into tomato, potato, corn, or other popular components of the human diet, 15 leads to human health benefits, such as reduced cancer risk, reduced incidence of osteoporosis, and treatment for alcoholism. Alternatively, introducing infection-inducible isoflavonoid biosynthesis into non-legumes qualitatively complements these  
30 plants' phytoalexin defenses against microbial pathogens, whereas over-expression of the isoflavonoid pathway in legumes quantitatively increases this defense response. 20 Finally, modifying the extent of production of isoflavonoids in legume roots positively  
35 impacts nodulation efficiency and therefore plant yield.



## Claims

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**WE CLAIM:**

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1. A method for introducing into a naturally non-isoflavonoid-producing plant species the enzyme catalyzing the aryl migration of a flavanone to form an isoflavanone intermediate or an isoflavone, comprising:

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5 introducing a DNA segment encoding said enzyme into said plant to form a transgenic plant, wherein said transgenic plant expresses said DNA segment under the control of a suitable constitutive or inducible promoter when said transgenic plant is exposed to conditions which permit expression.

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2. The method of Claim 1, wherein said DNA segment comprises isolated genomic DNA.

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3. The method of Claim 1, wherein said DNA segment comprises recombinant DNA.

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4. The method of Claim 1, 2 or 3, wherein said DNA segment comprises a CYP93C gene.

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5. The method of Claim 4, wherein said DNA segment consists essentially of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1.

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6. The method of Claim 1, 2 or 3, wherein said DNA segment comprises a *Medicago truncatula* homolog of a CYP93C gene.

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7. The method of Claim 6, wherein said DNA segment consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

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8. The method of Claim 1, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant to cause in vivo formation of daidzein or a daidzein derivative.

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9. The method of Claim 2, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant to cause in vivo formation of daidzein or a daidzein derivative.

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10. The method of Claim 3, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant to cause in vivo formation of daidzein or a daidzein derivative.

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11. The method of Claim 8, 9 or 10, wherein said plant is further transformed to comprise said chalcone synthase, chalcone reductase, and chalcone isomerase genes.

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12. The method of Claim 1, 2, 3, 8, 9 or 10, wherein said plant further comprises downstream genes to metabolize said formed isoflavanone intermediate or isoflavone to biologically active isoflavonoid derivatives or conjugates.

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13. The method of Claim 12, wherein said downstream gene is selected from the group consisting of isoflavone *O*-methyltransferase, isoflavone 2'-hydroxylase, isoflavone reductase, and vestitone reductase.

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14. The method of Claim 13, wherein said plant comprises downstream gene 4'-*O*-methyltransferase to form biochanin A or a biochanin A derivative.

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15. The method of Claim 1, 2, 3, 5, 7, 8, 9, 10, 13 or 14, wherein said flavanone is liquiritigenin.

16. The method of Claim 4, wherein said flavanone is liquiritigenin.

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17. The method of Claim 6, wherein said flavanone is liquiritigenin.

18. The method of Claim 11, wherein said flavanone is liquiritigenin.

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19. The method of Claim 12, wherein said flavanone is liquiritigenin.

20. The method of Claim 1, 2, 3, 5, 7, 8, 9, 10, 13 or 14, wherein said flavanone is naringenin.

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21. The method of Claim 4, wherein said flavanone is naringenin.

22. The method of Claim 6, wherein said flavanone is naringenin.

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23. The method of Claim 11, wherein said flavanone is naringenin.

24. The method of Claim 12, wherein said flavanone is naringenin.

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25. A method for increasing the level of isoflavonoid compounds in naturally isoflavonoid-producing plants comprising:

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5 introducing a DNA segment encoding the enzyme catalyzing the aryl migration of a flavanone to yield an isoflavonoid to form a transgenic plant, wherein said transgenic plant expresses said DNA segment under the control of a suitable constitutive or inducible promoter when said transgenic plant is exposed to conditions which permit expression.

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26. The method of Claim 25, wherein said isoflavonoid is selected from the group consisting of an isoflavanone intermediate, an isoflavone, an isoflavone derivative, and an isoflavone conjugate.

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27. The method of Claim 25, wherein said DNA segment comprises isolated genomic DNA.

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28. The method of Claim 26, wherein said DNA segment comprises isolated genomic DNA.

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29. The method of Claim 25, wherein said DNA segment comprises recombinant DNA.

30. The method of Claim 26, wherein said DNA segment comprises recombinant DNA.

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31. The method of Claim 25, 26, 27, 28, 29 or 30, wherein said DNA segment comprises a CYP93C gene.

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32. The method of Claim 31, wherein said DNA segment consists essentially of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1.

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33. The method of Claim 25, 26, 27, 28, 29 or 30, wherein said DNA segment is a *Medicago truncatula* homolog of a CYP93C gene.

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34. The method of Claim 33, wherein said DNA segment consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

20

35. The method of Claim 25, 26, 27, 28, 29, 30, 32 or 34, wherein said flavanone is liquiritigenin.

36. The method of Claim 31, wherein said flavanone is liquiritigenin.

25

37. The method of Claim 33, wherein said flavanone is liquiritigenin.

38. The method of Claim 25, 26, 27, 28, 29, 30, 32 or 34, wherein said flavanone is naringenin.

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39. The method of Claim 31, wherein said flavanone is naringenin.

40. The method of Claim 33, wherein said flavanone is naringenin.

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41. A method for synthesizing an isoflavanone intermediate or an isoflavone from a flavanone by expressing a recombinant CYP93C gene segment in a suitable bacterial, fungal, algal, or insect cell system.

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42. The method of Claim 41, wherein said gene segment consists essentially of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1.

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43. The method of Claim 41, wherein said gene segment consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

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5 44. A method of reducing the levels of isoflavonoid compounds in a naturally  
isoflavonoid-producing plant comprising introducing and expressing an antisense or  
gene silencing construct that contains an intact CYP93C gene or segments thereof into  
10 said plant.

45. The method of Claim 44, wherein said gene consists essentially of the  
sequence from about nucleotide 36 to about nucleotide 1598 of the sequence depicted  
15 in SEQ ID NO:1.

46. The method of Claim 44, wherein said gene consists essentially of the  
sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted  
20 in SEQ ID NO:4.

47. A naturally non-isoflavonoid-producing plant cell transformed by  
introducing a DNA segment encoding the enzyme catalyzing the aryl migration of a  
25 flavanone to form an isoflavanone intermediate or an isoflavone, wherein said  
transgenic plant cell expresses said DNA segment under the control of a suitable  
5 constitutive or inducible promoter when exposed to conditions which permit  
expression.

48. The plant cell of Claim 47, wherein said DNA segment comprises isolated  
genomic DNA.

49. The plant cell of Claim 47, wherein said DNA segment comprises  
35 recombinant DNA.

50. The plant cell of Claim 47, 48 or 49, wherein said DNA segment  
40 comprises a CYP93C gene.

51. The plant cell of Claim 50, wherein said DNA segment consists essentially  
of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence  
45 depicted in SEQ ID NO:1.

52. The plant cell of Claim 47, 48 or 49, wherein said DNA segment  
comprises a *Medicago truncatula* homolog of a CYP93C gene.

5 53. The plant cell of Claim 52, wherein said DNA segment consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

10 54. The plant cell of Claim 47, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant cell to cause in vivo formation of daidzein or a daidzein derivative.

15 55. The plant cell of Claim 48, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant cell to cause in vivo formation of daidzein or a daidzein derivative.

20 56. The plant cell of Claim 49, wherein chalcone synthase, chalcone reductase, and chalcone isomerase genes are also expressed in said plant cell to cause in vivo formation of daidzein or a daidzein derivative.

25 57. The plant cell of Claim 54, 55 or 56, wherein said plant cell is further transformed to comprise said chalcone synthase, chalcone reductase, and chalcone isomerase genes.

30 58. The plant cell of Claim 47, 48, 49, 54, 55 or 56, wherein said plant cell further comprises downstream genes to metabolize said formed isoflavanone intermediate or isoflavone to biologically active isoflavonoid derivatives or conjugates.

35 59. The plant cell of Claim 58, wherein said downstream gene is selected from the group consisting of isoflavone *O*-methyltransferase, isoflavone 2'-hydroxylase, isoflavone reductase, and vestitone reductase.

40 60. The plant cell of Claim 59, wherein said plant cell comprises downstream gene 4'-*O*-methyltransferase to cause in vivo formation of biochanin A or a biochanin A derivative.

5 61. A naturally isoflavonoid-producing plant cell transformed by introducing a  
DNA segment encoding the enzyme catalyzing the aryl migration of a flavanone to  
yield an isoflavonoid to form a transformed plant cell, wherein said transformed plant  
10 cell expresses said DNA segment under the control of a suitable constitutive or  
5 inducible promoter when exposed to conditions which permit expression.

15 62. The plant cell of Claim 61, wherein said isoflavonoid is selected from the  
group consisting of an isoflavanone intermediate, an isoflavone, an isoflavone  
derivative, and an isoflavone conjugate.

20 63. The plant cell of Claim 61, wherein said DNA segment comprises isolated  
genomic DNA.

25 64. The plant cell of Claim 62, wherein said DNA segment comprises isolated  
genomic DNA.

30 65. The plant cell of Claim 61, wherein said DNA segment comprises  
recombinant DNA.

35 66. The plant cell of Claim 62, wherein said DNA segment comprises  
recombinant DNA.

40 67. The plant cell of Claim 61, 62, 63, 64, 65 or 66, wherein said DNA  
segment comprises a CYP93C gene.

45 68. The plant cell of Claim 67, wherein said DNA segment consists essentially  
of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence  
depicted in SEQ ID NO:1.

50 69. The plant cell of Claim 61, 62, 63, 64, 65 or 66, wherein said DNA  
segment is a *Medicago truncatula* homolog of a CYP93C gene.

55 70. The plant cell of Claim 69, wherein said DNA segment consists essentially  
of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence  
depicted in SEQ ID NO:4.



5 71. A transgenic plant cell having reduced levels of isoflavonoid compounds, said plant cell transformed by introducing an antisense or gene silencing construct that contains an intact CYP93C gene or segments thereof into said plant cell.

10 72. The plant cell of Claim 71, wherein said gene consists essentially of the sequence from about nucleotide 36 to about nucleotide 1598 of the sequence depicted in SEQ ID NO:1.

15 73. The plant cell of Claim 71, wherein said gene consists essentially of the sequence from about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4.

20 74. An isolated gene or DNA segment comprising a portion which encodes a cytochrome P450 of the CYP93 family that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said portion  
25 consists essentially of about nucleotide 36 to about nucleotide 1598 of the sequence  
5 depicted in SEQ ID NO:1.

30 75. The gene or DNA segment of Claim 74, wherein said gene is the soybean gene encoding the enzyme catalyzing the aryl migration of liquiritigenin.

76. The gene or DNA segment of Claim 74, wherein said gene is the soybean gene encoding the enzyme catalyzing the aryl migration of naringenin.

35 77. A protein encoded by a portion of an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said portion consists  
40 essentially of about nucleotide 36 to about nucleotide 1598 of the sequence depicted in  
5 SEQ ID NO:1.

45 78. An isolated gene or DNA segment comprising a portion which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said portion is a *Medicago truncatula* homolog of a CYP93C gene.

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79. The gene or DNA segment of Claim 78 consisting essentially of about nucleotide 92 to about nucleotide 1657 of the sequence depicted in SEQ ID NO:4

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80. The gene or DNA segment of Claim 78, wherein said gene is the *Medicago truncatula* gene encoding the enzyme catalyzing the aryl migration of liquiritigenin.

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81. The gene or DNA segment of Claim 79, wherein said gene is the *Medicago truncatula* gene encoding the enzyme catalyzing the aryl migration of liquiritigenin.

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82. The gene or DNA segment of Claim 78, wherein said gene is the *Medicago truncatula* gene encoding the enzyme catalyzing the aryl migration of naringenin.

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83. The gene or DNA segment of Claim 79, wherein said gene is the *Medicago truncatula* gene encoding the enzyme catalyzing the aryl migration of naringenin.

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84. A protein encoded by a portion of an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said portion is a *Medicago truncatula* homolog of a CYP93C gene.

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85. A food comprising edible transgenic plant material capable of being ingested for its nutritional value, said transgenic plant is transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits increased levels of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment.

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86. A food comprising at least one isoflavonoid, wherein said isoflavonoid is isolated from a transgenic plant transformed with an isolated gene or DNA segment

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5 which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone  
to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant  
5 exhibits increased levels of an isoflavonoid when compared to the level of said  
10 isoflavonoid in plants of the same species which do not comprise said isolated gene or  
DNA segment.

15 87. A composition comprising at least a portion of a transgenic plant  
transformed with an isolated gene or DNA segment which encodes a cytochrome P450  
that can catalyze the aryl migration of a flavanone to yield an isoflavanone  
intermediate or an isoflavone, wherein said transgenic plant exhibits increased levels  
5 of an isoflavonoid when compared to the level of said isoflavonoid in plants of the  
20 same species which do not comprise said isolated gene or DNA segment, said  
composition suitable for ingestion as a food stuff, a nutritional supplement, an animal  
feed supplement, or a nutraceutical.

25 88. A composition comprising an isoflavonoid suitable for administration as a  
food stuff, a nutritional supplement, an animal feed supplement, a nutraceutical, or a  
pharmaceutical, said isoflavonoid isolated from at least a portion of a transgenic plant  
30 transformed with an isolated gene or DNA segment which encodes a cytochrome P450  
5 that can catalyze the aryl migration of a flavanone to yield an isoflavanone  
intermediate or an isoflavone, wherein said transgenic plant exhibits increased levels  
of an isoflavonoid when compared to the level of said isoflavonoid in plants of the  
35 same species which do not comprise said isolated gene or DNA segment.

40 89. A method of increasing the nutritional value of a plant by transforming  
said plant with an isolated gene or DNA segment which encodes a cytochrome P450  
that can catalyze the aryl migration of a flavanone to yield an isoflavanone  
intermediate or an isoflavone, wherein said transgenic plant exhibits increased levels  
5 of an isoflavonoid when compared to the level of said isoflavonoid in plants of the  
45 same species which do not comprise said isolated gene or DNA segment.

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90. A method of using a transgenic plant transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment, to provide a nutraceutical benefit to a human or animal administered said isoflavonoid.

91. The method of claim 90, wherein said isoflavonoid is administered by ingestion of at least a portion of said plant.

92. The method of claim 90, wherein said isoflavonoid is administered by ingestion of a composition comprising an isoflavonoid isolated from said plant.

93. A method of using an isoflavonoid isolated from a transgenic plant transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment, to provide a pharmaceutical benefit to a patient administered said isoflavonoid.

94. A method of increasing disease resistance in a plant by transforming said plant with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment.

5 95. A method of increasing nodulation efficiency of a leguminous plant by transforming said plant with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an  
10 isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an increased level of an isoflavonoid released from the roots of said transgenic plant  
5 when compared to the level of the isoflavonoid released from the roots of plants of the same species which do not comprise said isolated gene or DNA segment.

15 96. A leguminous transgenic plant exhibiting increased nodulation efficiency, wherein said transgenic plant is transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone  
20 to yield an isoflavanone intermediate or an isoflavone, and wherein said transgenic plant exhibits an increased level of an isoflavonoid released from the roots of said  
5 transgenic plant when compared to the level of the isoflavonoid released from the roots of plants of the same species which do not comprise said isolated gene or DNA  
25 segment.

30 97. A method of increasing bacterial or fungal symbiosis in a plant by transforming said plant with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an  
isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an  
5 increased level of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment.  
35

40 98. A transgenic plant exhibiting an increased level of bacterial or fungal symbiosis, wherein said transgenic plant is transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a  
flavanone to yield an isoflavanone intermediate or an isoflavone, and wherein said  
5 transgenic plant exhibits an increased level of an isoflavonoid when compared to the level of said isoflavonoid in plants of the same species which do not comprise the  
45 isolated gene or DNA segment.

5 99. A transgenic plant comprising at least one recombinant DNA sequence  
encoding a cytochrome P450 that can catalyze the aryl migration of a flavanone to  
yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant  
10 exhibits an increased level of an isoflavonoid when compared to the level of said  
5 isoflavonoid in plants of the same species which do not comprise said recombinant  
DNA sequence.

15 100. Seed from a transgenic plant comprising at least one recombinant DNA  
sequence encoding a cytochrome P450 that can catalyze the aryl migration of a  
flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said  
transgenic plant exhibits an increased level of an isoflavonoid when compared to the  
20 5 level of said isoflavonoid in plants of the same species which do not comprise said  
recombinant DNA sequence.

25 101. Progeny from a transgenic plant comprising at least one recombinant  
DNA sequence encoding a cytochrome P450 that can catalyze the aryl migration of a  
flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said  
transgenic plant exhibits an increased level of an isoflavonoid when compared to the  
30 5 level of said isoflavonoid in plants of the same species which do not comprise said  
recombinant DNA sequence.

35 102. Progeny from seed of a transgenic plant comprising at least one  
recombinant DNA sequence encoding a cytochrome P450 that can catalyze the aryl  
migration of a flavanone to yield an isoflavanone intermediate or an isoflavone,  
wherein said transgenic plant exhibits an increased level of an isoflavonoid when  
40 5 compared to the level of said isoflavonoid in plants of the same species which do not  
comprise said recombinant DNA sequence.

45 103. Use of a transgenic plant transformed with an isolated gene or DNA  
segment which encodes a cytochrome P450 that can catalyze the aryl migration of a  
flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said  
transgenic plant exhibits an increased level of an isoflavonoid when compared to the  
5 5 level of said isoflavonoid in plants of the same species which do not comprise said

5 isolated gene or DNA segment, for the preparation of a nutraceutical preparation for achieving a nutritional effect.

10 104. Use of a transgenic plant transformed with an isolated gene or DNA segment which encodes a cytochrome P450 that can catalyze the aryl migration of a flavanone to yield an isoflavanone intermediate or an isoflavone, wherein said transgenic plant exhibits an increased level of an isoflavonoid when compared to the  
15 5 level of said isoflavonoid in plants of the same species which do not comprise said isolated gene or DNA segment, for the preparation of a pharmaceutical preparation for achieving a therapeutic effect.

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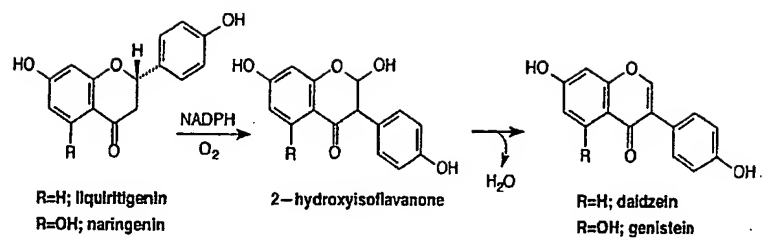


Fig. 1



2/15

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Fig. 2

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46 MHML.GPLLHQSFHNLSHRYGPLFSLNFGSVLCVVASTPHFAKQLLOTNE 94
98 ATSFNTRFQTSAIRRLTYDSSVAMVPFGPYWKFVRKLMNDLLNATTVNK 147
      .|| | :...:|:|:|:| | :| |:|:| |:| | . :|
95 .LAFNCRIESTAVKKLTYESSLAFAPYGDYWRFIKKLSMNELLGSRINN 143
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144 FQHLRAQETHQLRLLSNRARAFEAVNITEELLKLTNNVISIMMVGEAE 193
198 IRDIAREVLKIFGEYSLTDFIWPLKHLKVGKYEKRIDDILNKFDPPVERV 247
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194 ARDVVRDVTIEIFGEFNVSDFIWLFKKMDLQGFGRKIEDLFQFDTLVERI 243
248 IKKRREIVR.RRKNGEVVE.GEVSGV..FLDTLLEFAEDETMEIKITKH 293
      | || : : ||:| | | | : || | : || | ||| : |
244 ISKREQTRKDRRRNGKKGEQSGDGI RDL DILLDCTEDENSEIKIQRVH 293
294 IKGLVVDFFSAGTDSTAVATEWALAEINNPKVLEKAREEVYVVGKDRL 343
      || |: .|||.|||.||: .||| ||: | ||: ||: .|||
294 IKALIMDFFTAGTDTTAISTEWALVELVKKPSVLQKVREEIDNVVGKDRL 343
344 VDEVDTQNLPHYIRAIVKETFRMHPLPVVKRKCTEECEINGYVIPEGALI 393
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344 VEESDCPNLPYLQAILKETFRLHPPVPMVTRRCVAECTVENYVIPEDSLL 393
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394 FVNVSIGRNPKEWDNPLEFRPERFLKLEGD.SSGVVDVRGSHFQLLPFG 442
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Fig. 3

4/15

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1801 TATTCATTAT T

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Fig. 4

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CYP93C1v2	1	M	L	E	L	A	L	G	L	L	V	L	A	L	F	L	H	R	P	T	P	T	A	K	S	K	A	L	R	H	L	P	N	P <td>P <td>S <td>P <td>K <td>P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td></td></td></td></td></td>	P <td>S <td>P <td>K <td>P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td></td></td></td></td>	S <td>P <td>K <td>P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td></td></td></td>	P <td>K <td>P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td></td></td>	K <td>P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td></td>	P <td>R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td></td>	R <td>L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td></td>	L <td>P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td></td>	P <td>F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td></td>	F <td>I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td></td>	I <td>G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td></td>	G <td>H <td>L <td>H <td>L <td>50</td> </td></td></td></td>	H <td>L <td>H <td>L <td>50</td> </td></td></td>	L <td>H <td>L <td>50</td> </td></td>	H <td>L <td>50</td> </td>	L <td>50</td>	50		
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**Fig. 5**

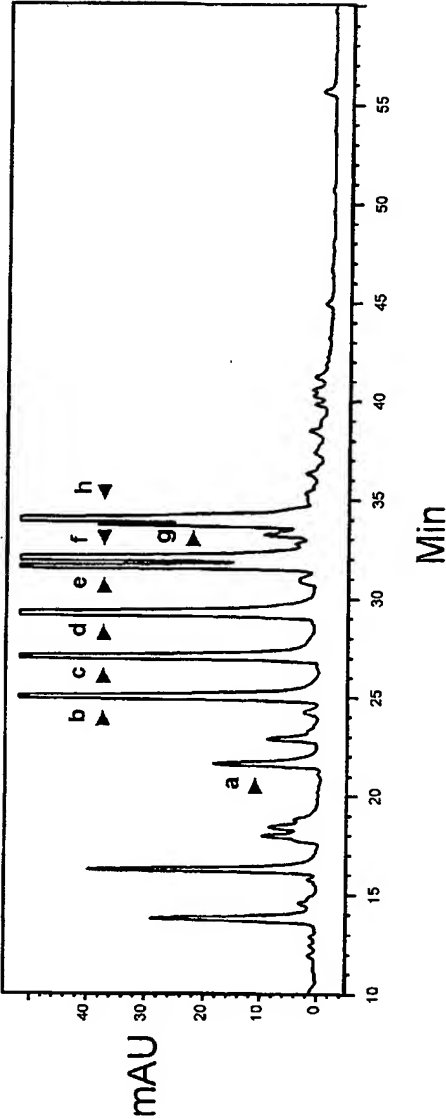


Fig. 6A

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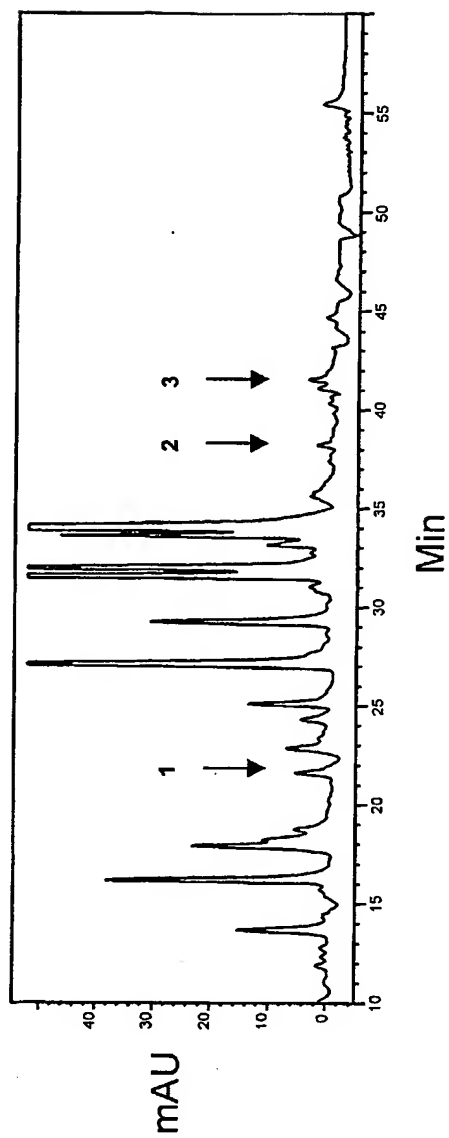


Fig. 6B

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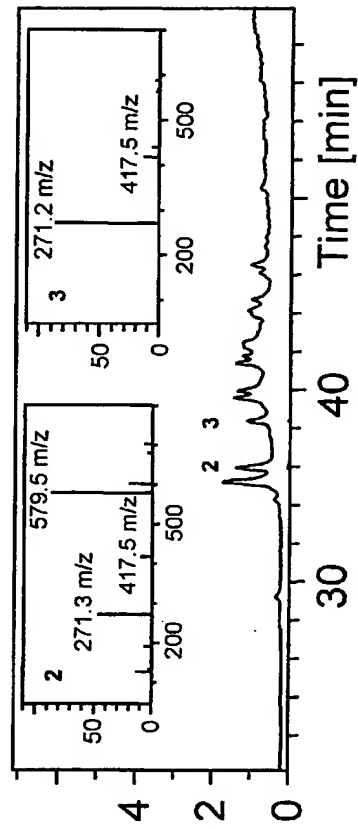


Fig. 6C

9/15

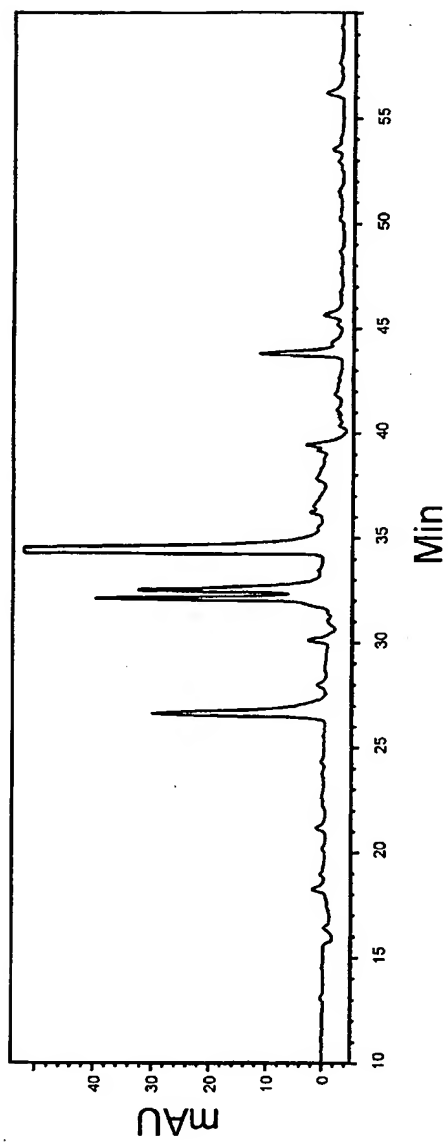


Fig. 7A



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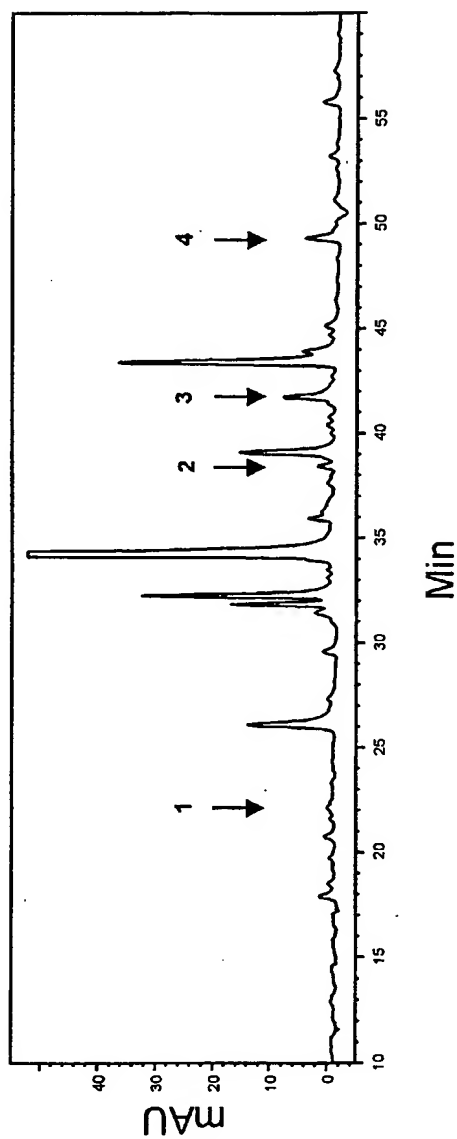


Fig. 7B

11/15

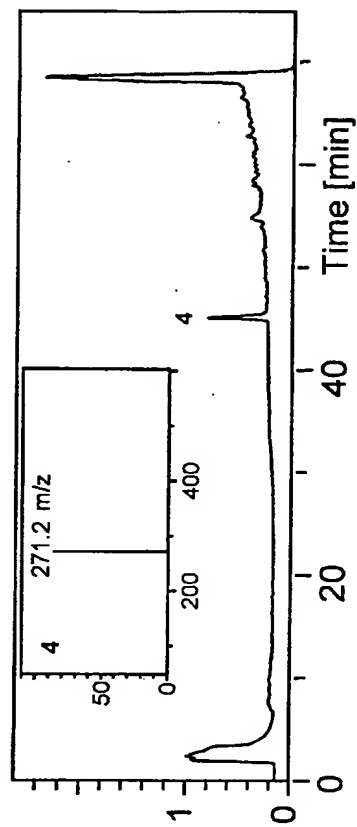


Fig. 7C

12/15

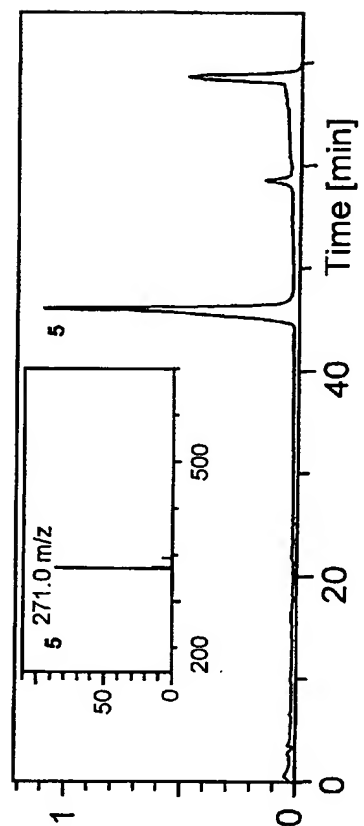


Fig. 7D

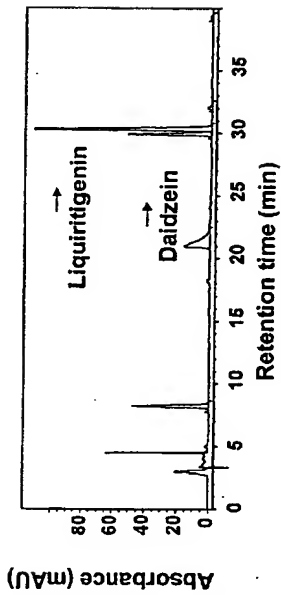


Fig. 8A

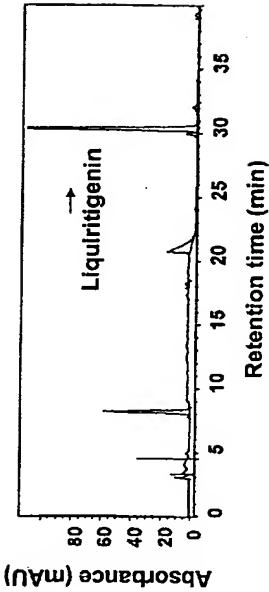


Fig. 8B

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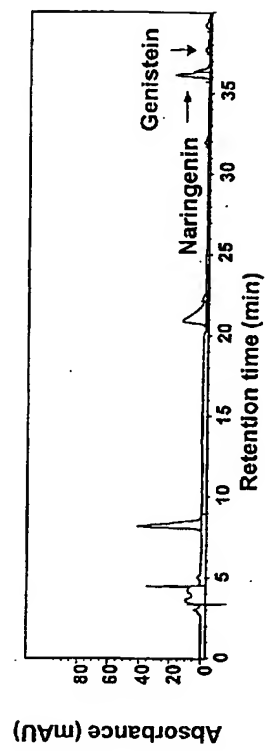


Fig. 8C

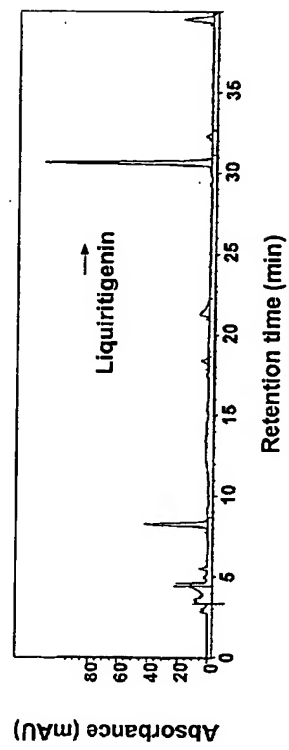


Fig. 8D

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Fig. 9A

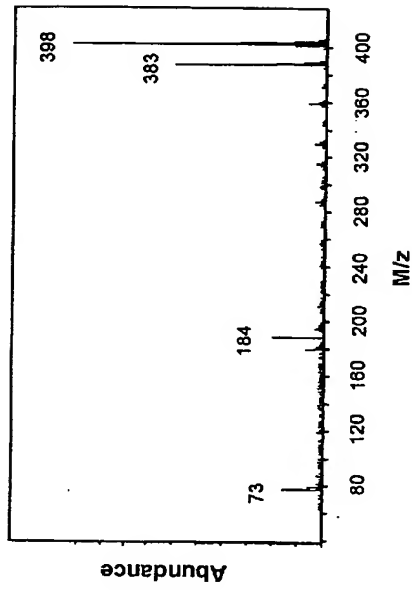
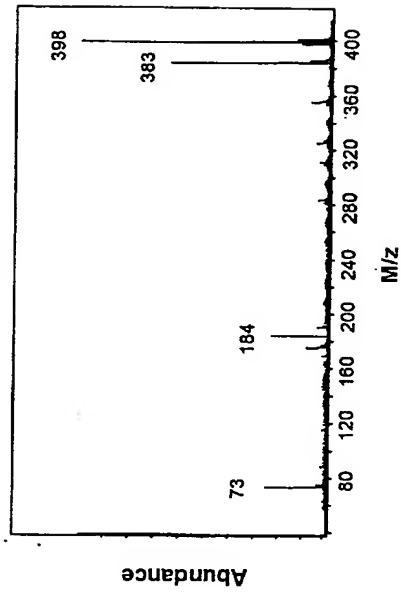


Fig. 9B



## SEQUENCE LISTING

<110> THE SAMUEL ROBERTS NOBLE FOUNDATION, INC.  
STEELE, Christopher L.  
DIXON, Richard A.

<120> GENETIC MANIPULATION OF ISOFLAVONOIDS

<130> 11137/05002

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# INTERNATIONAL SEARCH REPORT

International Application No. <b>PCT/US 00/05915</b>				
<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC 7 C12N15/53 C12N15/82 C12N15/11 C12N9/02 C12N5/10 A01H5/00 A01H5/10 A23L1/00				
According to International Patent Classification (IPC) or to both national classification and IPC				
<b>B. FIELDS SEARCHED</b> Minimum documentation searched (classification system followed by classification symbols) IPC 7 C12N A01H A23L				
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched				
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, BIOSIS				
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>				
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
X	SIMINSZKY B. ET AL.: "Cytochrome P450 monooxygenase CYP93C1p from soybean; AC AF022462" EBI DATABASE, 8 January 1998 (1998-01-08), XP002143672 cited in the application the whole document & SIMINSZKY B. ET AL.: "Expression of a soybean cytochrome P450 monooxygenase cDNA in yeast and tobacco enhances the metabolism of phenylurea herbicides" PNAS, U.S.A., vol. 96, February 1999 (1999-02), pages 1750-1755, XP002100400 the whole document --- -/--	74-77		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C.				
<input checked="" type="checkbox"/> Patent family members are listed in annex.				
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "Z" document member of the same patent family				
Date of the actual completion of the international search 27 July 2000		Date of mailing of the international search report 10/08/2000		
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Int'l. Patent Application No.  
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